55: Estimation of Snow Extent and Snow Properties

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Important advances have been made in the measurement of seasonal snow cover since the advent of satellite remote sensing in the mid 1960s. Data from the visible, near-infrared, infrared, and microwave portions of the electromagnetic spectrum have proven useful for measuring different properties of snow. In terms of snow mapping, sensors employing visible and near-infrared wavelengths are now capable of accurately and reliably measuring snow-cover extent with a spatial resolution of up to 250 m on a daily basis, and even higher resolution for less-frequent coverage. Passive-microwave data, available since the 1970s, have been utilized for measuring snow extent, depth and snow-water equivalent (SWE), though at a coarse spatial resolution compared to visible data, while active-microwave sensors such as scatterometers, provide valuable information on snowpack ripening. Capabilities of synthetic-aperture radar (SAR) data for snow-cover studies are still being explored, however, bands on current satellite SAR sensors are not ideal for measuring snow cover. Remote sensing data of snow cover are now well suited for use in hydrologic and general-circulation models. Inclusion of remotely-sensed data significantly enhances our understanding of the Earth's weather and climate, and decadal-scale climate change. Future improvements include refinement of snow-cover extent measurements, minimizing SWE errors, and improving our ability to ingest remote sensing data of snow into models.

INTRODUCTION

Satellite remote-sensing technology has virtually revolutionized the study of snow cover. The high albedo of snow presents a good contrast with most other natural surfaces (except clouds), and therefore is easily detected by many satellite sensors. Weekly snow mapping of the Northern Hemisphere using National Oceanographic and Atmospheric Administration (NOAA) satellite data began in 1966 and continues today in the United States, but with improved resolution and on a daily basis (Matson *et al.*, 1986; Ramsay, 1998; Carroll *et al.*, 2001). In addition, using Earth Observing System (EOS) Moderate Resolution Imaging Spectroradiometer (MODIS) data, beginning in early 2000, global snow cover has been mapped on a daily basis at a spatial resolution of up to 500 m (Hall *et al.*, 2002a).

In addition to the visible/near-infrared data, from MODIS and NOAA satellite sensors, both passive and active microwave data have been useful for mapping snow and determining snow wetness and snow water equivalent (SWE) (Ulaby and Stiles, 1980) since the early 1970s. Using passive microwave data, snow extent, and SWE may be estimated globally on a daily basis since the launch of the Nimbus-7 Scanning Multichannel Microwave Radiometer (SMMR) (Chang *et al.*, 1987), and continuing with the May 2002 launch of the Advanced Microwave Scanning Radiometer (AMSR) (Kelly *et al.*, 2003). Active-microwave sensors, such as from the NASA scatterometer (NSCAT), are especially useful for detecting snowpack ripening (Nghiem and Tsai, 2001).

The geographical extent of snow cover over the Northern Hemisphere varies from a maximum of $\sim 46 \times 10^6\,\mathrm{km}^2$ in January and February to a minimum of $\sim 4 \times 10^6\,\mathrm{km}^2$ in August; between 60 and 65% of winter snow cover is found over Eurasia, and most midsummer snow cover is in Greenland (Frei and Robinson, 1999). Numerous studies have shown the importance of accurate measurements of snow and ice parameters as they relate to the Earth's climate and climate change (for example, see Martinelli, 1979; Dewey and Heim, 1981 and 1983; Barry, 1983, 1984, and 1990; Dozier, 1987; Ledley *et al.*, 1999; Foster *et al.*, 1987 and 1996; Serreze *et al.*, 2000; Dozier and Painter, 2004). Measurements have become increasingly sophisticated over time. In addition, as the length of the satellite record increases, it becomes easier to determine trends that have climatic importance.

Three of the most important properties of a snow cover are depth, density, and water equivalent (Pomeroy and Gray, 1995). If the snow depth and density are known, then the SWE may be calculated. SWE is a hydrologically important parameter as it determines the amount of water that will be available as snowmelt.

After introducing snow as a medium, and reviewing

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its optical and microwave properties, we will show how remote sensing is used to study snow-covered area, SWE, snow wetness and snow albedo, and discuss the parameterization of snow in hydrologic and general circulation models (GCMs).

Future Directions and Conclusions

Mapping snow cover areal extent using satellite observations is relatively mature and well validated (see, e.g., Robinson, 1993, 1999; Hughes *et al.*, 1996; Frei *et al.*, 1999; Hall *et al.*, 2002a; Brown *et al.*, 2003; Mauer *et al.*, 2003). Recent global water and climate system studies have begun to examine the link between snow cover areal extent and atmospheric dynamics. For example, Cohen and Entekhabi (1999) investigated the link between early season snow extent in Eurasia and the dynamics of the Siberian high. Saunders *et al.* (2003) show a link between summer snow extent and the winter North Atlantic Oscillation. These studies are important for our understanding of the role of snow in the Earth's hydrological cycle and how it affects human sustainability, especially in regions that are heavily dependent on snowmelt runoff for water supply.

The methodology to map global SWE from remote-sensing instruments is less mature. While microwave remote-sensing observations are helping to advance our ability to effectively characterize water storage in snowpacks, there remain uncertainties about the retrievals from these instruments. Historically, the frequency configurations of space borne active radar systems have produced measurements that are sensitive to the presence or absence of wet snow only and little or no direct information about SWE can be determined from these instruments. Satellite passive microwave measurements now have a 25- year record from which SWE can be estimated. However, with the characteristically large instantaneous fields of view that characterize these instruments (tens of kilometers), the uncertainties associated with SWE estimates are difficult to quantify, and, therefore, are still under investigation. Studies have shown that in noncomplex terrain with low-stand vegetation, reasonable estimates of SWE can be obtained from passive microwave measurements. In other terrain types, however, larger uncertainties persist.

In order to characterize snow water storage, new and improved satellite instrument measurement techniques need to be developed, especially for instruments in the microwave part of the electromagnetic spectrum that are sensitive to snow volume. Ku-band radar measurements are sensitive to SWE and could be developed to resolve fine spatial variations of SWE (tens of meters) through SAR technology. For passive microwave measurements, the relatively low spatial resolution is a key cause of uncertainties in the estimation of SWE. Only through technology improvements in antenna design can instantaneous fields of view be significantly improved, thus increasing the spatial resolution (e.g. Doiron *et al.*, 2004).

With improvements in microwave instrument and measurement techniques of SWE, the uncertainties and errors in SWE estimates will be reduced providing more confidence in our ability to estimate snow water storage throughout the year. If these technology developments come to fruition and new, "more SWE-capable" microwave missions overlap with the current and planned global multidisciplinary instruments, such as the available AMSR-E and the proposed Conical Scanning Microwave Imager/Sounder (CMIS) planned for National Polar-orbiting Operational Environmental Satellite System (NPOESS), the benefits could be great (Kelly *et al.*, 2004). Local scale SWE characterization would be possible; the prospect of combining high spatial resolution-accurate SWE measurements with sophisticated numerical land surface models may then be possible, and is a very exciting one from the water resource management perspective.

Satellite remote sensing has been used to map snow cover for nearly 40 years. Decade-scale CDR-quality records of snow-covered area are already in existence for the Northern Hemisphere (Robinson and Frei, 2000) and are useful in climate models, however, problems exist in developing a CDR for SWE (Armstrong and Brodzik, 2001; Derksen *et al.*, 2003), as discussed above. We can now extend the snow-covered area record using SMMR, SSM/I MODIS, and AMSR data to the global scale, and provide CDR-quality maps of snow-covered area, and continue to study the development of CDR-quality datasets of SWE and snow albedo using visible, near infrared, and passive microwave sensors such as the MODIS and AMSR.

The trend has been toward increasingly automatically processed quantitative maps with error bars provided. Automated processing is necessary so that consistent products can be derived from the observations and long duration data sets might ultimately be available for long-term water-cycle studies. The error estimates associated with snow products are also essential if the products are to be used effectively in combination with catchment-based land surface or climate models. This is because models that require snow-state parameters often require the errors associated with the estimated snow states, especially if data assimilation techniques are used to generate blended products. Whether the snow products are used for initial conditioning or as a forcing variable in a model, or whether the products are used in their own right, the role of remotely sensed observations of snow will continue to be important and is set to play an increasingly important role in climate and hydrological forecasting.

Future sensors will permit automated algorithms to be used to create maps that are consistent with existing maps so that the confidence level of the long-term (~40 year) record is high. The quality allows them to be amenable to comparison with long-term records of other geophysical parameters such as global sea ice, and for input to general circulation models.